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THE ANNUAL VARIATION OF ATMOSPHERIC PRESSURE IN THE UNITED STATES

(STUDIES ON CLIMATE AND CROPS: 6)*

By HENRYK ARCTOWSKI

The ordinary maps representing the distribution of atmospheric pressure over the globe or over certain parts of the earth's surface give the mean heights of the barometer reduced to 0°C. (32°F.), the sea level and the normal gravity at 45° latitude. The correction to a standard temperature is necessary to avoid the systematic instrumental error due to the expansion of mercury, which is a function of temperature. The correction to the sea level, on the contrary, although necessary for the tracing of maps, is to a certain extent artificial, since, in reality, it leads to a representation of the distribution of atmospheric pressure as it would be if the earth's surface were different from what it is. In the case of continental areas, with extensive plateaus and mountain ranges, as in the west of the United States, for example, the difference may be great for a large number of stations between the corrected sea level pressures and those really observed. By reducing the readings of the barometer to sea level we add to the observed weight of the column of air, above the surface of the ground, the weight of an assumed column of air extending (under the given condition of temperature and vapor tension) beneath the surface of the ground down to sea level. Of course the thickness of the atmosphere above the summit of a mountain is less than at the foot of the mountain; the pressure at the summit is therefore smaller than down below. If we inscribed on a map the observed values we would simply obtain a likely resemblance of the hypsometrical map and such a representation of things would be of no use. But the column of air beneath the surface of the ground does not exist, and, therefore, if for the purposes of our investigations we have to study the transport of air masses,—from one hemisphere to another for example[1]—the unreduced values must be used.

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* For previous papers in this series see *Bull.*, Vol. 42, 1910, pp. 270-282 and 480-495, Vol. 44, 1912, pp. 598-606 and 745-760, and Vol. 45, 1913, pp. 117-131.

[1] Researches on this particular subject have been made long ago by W. Koeppen, J. Kleiber and A. v. Tillo. The most important and more recent papers on the subject are:—O. Baschin: Zur Frage des jahreszeitlichen Luftaustausches zwischen beiden Hemisphären, *Zeitschr. der Gesell. für Erdkunde zu Berlin*, Vol. 30, 1895, pp. 368-374;—R. Spitaler: Die periodischen Luft-

In my former investigations on atmospheric pressure I have shown how important some of the abnormal changes may be.[2] So far I have only taken into consideration yearly means. To study seasonal anomalies, or those concerning a month or two, it was necessary to begin the researches by an investigation of the normal seasonal changes.

The seasonal transport of air masses over continental areas is a complicated phenomenon, and, in my opinion, the knowledge of these complications is of real importance in the study of climatic variations.

Imagine a temporary change in the quantity of energy radiated from the sun, a small variation of the "solar constant" during, let us say, a month of time. The thickness of the atmosphere above high plateaus is less than above low ground or the sea. The reaction of the change must therefore be felt differently at high altitudes than near sea level and a perturbation due to this difference must result. Now, all other conditions remaining the same, as far as may be, the reaction will again be of a quite different character according to the time of the year when it occurs, whether during the summer or the winter months. In summer, temperature being high, the atmosphere is expanded and the proportion of air above high level stations is therefore increased. The results of the observations taken at the summit of Pike's Peak (altitude: 14,111 feet), from 1874 until 1887, may serve as an illustration. The mean barometric height being 17.735 inches, the departures of the mean monthly means from this value are:[3]

January....	—0.263	May........	+0.028	September..	+0.199
February...	—0.250	June.......	+0.194	October.....	+0.065
March......	—0.194	July........	+0.323	November..	—0.094
April.......	—0.131	August.....	+0.310	December..	—0.181

The curve expressing these figures graphically is extremely regular and represents a simple oscillation, identical to that of the annual

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massenverschiebungen und ihr Einfluss auf die Lagenänderung der Erdachse, *Ergänzungsheft zu Petermanns Mitt. No. 137*, Gotha, 1901;—O. Baschin: Die geographische Verteilung des Luftdrucks und deren Aenderung vom Sommer zum Winter, *Zeitschr. der Gesell. für Erdkunde zu Berlin*, 1907, pp. 246-253;—W. Meinardus: Die mutmassliche mittlere Höhe des antarktischen Kontinents, *Petermanns Mitt.*, Vol. 55, 1909, pp. 304-309 and 355-360;—W. Koeppen: Die Verschiebungen der Atmosphäre im Jahreslaufe und die Höhe des antarktischen Kontinents, *Meteorol. Zeitschr*, 1910, p. 488. The seasonal changes of the distribution of atmospheric pressure in the northern hemisphere, reduced to sea level, may be studied from the maps of monthly normal departures from annual normal pressures published by H. H. C. Dunwoody, (Summary of Internat. Meteor. Observat., *Weather Bureau Bull. A.*, Washington, 1893.)

[2] *Comptes Rendus de l'Acad. des Sciences de Paris*, Vol. 148, 1909, p. 589.

[3] Frank H. Bigelow: Report on the Barometry of the United States, Canada and the West Indies, *Report of the Chief of the Weather Bureau, 1900-1901*, Vol. II., p. 558.

variation of temperature. In January, when the temperature is lowest, the atmospheric pressure is lowest at the summit of Pike's Peak simply because, the air being dense, a smaller amount of air surpasses the elevation of the mountain. In July and August, on the contrary, when the temperature is highest, the air is expanded, it is less dense; a greater proportion of the atmosphere is above the summit of the mountain and this is why the measured weight of air is greater.

It is obvious therefore that in the case of the North American continent, where high plateaus occupy large areas, the seasonal changes in the distribution of the air masses must present local characteristics of some interest.

To begin with, let us compare the curves of the adjoining diagram (Fig. 1) representing the annual variations of atmospheric pressure at some low-level stations along the Atlantic.[4] In Washington we notice a simple oscillation of the barometric height: it is lowest during May, June and July and highest in December and January. Going south the curves are more complicated: they show a tendency to adjust themselves to the double oscillation observed in Florida and Cuba, with a principal maximum in January and a less important one in July. Going north from Washington we again notice complications,

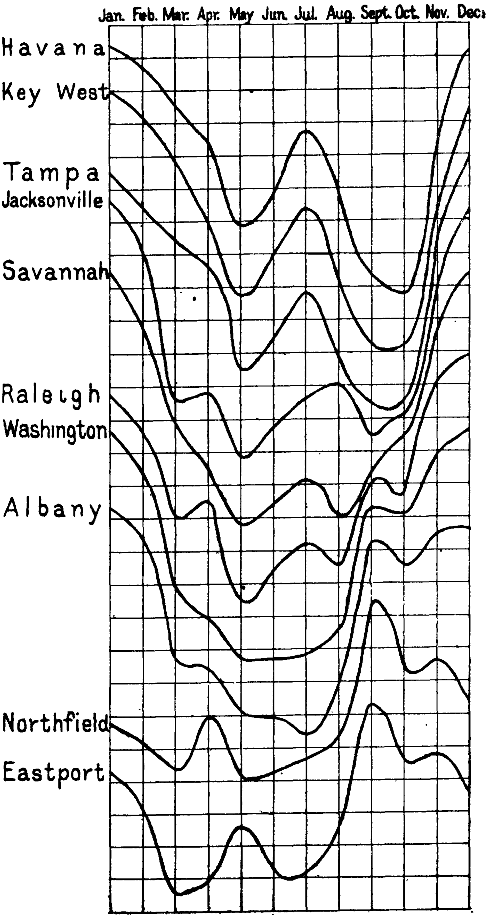

FIG. 1—Diagram representing the annual variation of atmospheric pressure at stations of low elevation along the Atlantic coast.

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[4] The monthly means utilized have been taken from the report by Bigelow cited above.

and the curve of Eastport is nearly the reversed curve of Key West.[5]

It is not only along the Atlantic coast that the annual variation presents such distinct types. In Amarillo, Tex., the barometer is below the average from January to June and above from July to December, with the minimum in March and the maximum in July. In Denver, Colo., we observe a simple and regular oscillation; minimum in March, and maximum in August; the same in Salt Lake City where the minimum occurs in May and the maximum in November; in Red Bluff, Cal., the same, but the mimimum occurs in August and the maximum in December. Farther north, in Tatoosh Island, in the state of Washington, we see just the contrary: maximum in July and minimum in December, but there the yearly variation is represented no more by a simple oscillation.

In order to understand the correlations between all of these different types of variations it is necessary to study the problem geographically. For this reason I have constructed a number of maps which I will now discuss. The figures utilized to draw these maps have all been taken from the tables designated Table 43 in Bigelow's report (pp. 429-623) giving, besides the results of the observations made from 1873 to 1899, the averages of the monthly and yearly means and the departures. Of course for the majority of stations the series of observations is shorter than the period of years taken into consideration by Bigelow. In many cases, therefore, the departures are far less correct than those where the series of observations is complete. This lack of accuracy, or defect of homogeneity, cannot, however, affect my deductions.

Taking the differences between the highest and lowest departures from the annual mean for each station and inscribing these differences on a map, it was easy to draw the lines of equi-amplitudes I do not reproduce this map, which represents the geographical distribution of the amplitudes of annual variation, since it can be easily described.

The highest yearly amplitudes occur on the frontier of Mexico. In Yuma, Ariz., the mean departures for January and June are +0.166 and —0.141, which makes an amplitude of 0.307. In Rio Grande City, Tex., the extreme departures are +0.128 and —0.103, also occurring in January and June. The disposition of the lines of equi-amplitudes show that four tongues or ridges of high values extend from Mexico, this center of greatest yearly variations, and gradually diminish toward the north. The first ridge follows the Californian valley and goes as far north as Tatoosh Island, Wash. The figures are: Yuma 0.307, Fresno 0.291, Sacramento 0.274, Red Bluff 0.273, Roseburg 0.125 and Tatoosh Isl. 0.131. The second ridge goes northeast from Yuma (Phoenix 0.277) and then turns north (Lander, Wyo., 0.209) and northwest (Boise, Idaho, 0.196). The third ridge starts from Rio Grande City, Tex., and follows the outline of the plateau region along the 97th meridian, as far as the Canadian border line. At Moorhead, Minn., the amplitude is still as high as 0.171. The fourth and least characteristic ridge follows the Atlantic coast and extends from the Gulf of Mexico to Nova Scotia.

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[5] The July maximum is subject to interesting variations. The average departure from the yearly mean is +0.008 inches at Key West. The extreme values were observed in 1877 and 1892, when the departures from the corresponding yearly means were —0.027 and +0.054. The changes in the yearly variation curves, and especially those of the July maximum, seem to demonstrate certain correlations with sun spot frequency.

Now, between these four ridges, like three fingers coming from the north, we have three characteristic lines of lowest values of the yearly amplitude, increasing from the north toward the south. Between the first and second ridge we note the figures: 0.073, 0.084, 0.135 for Seattle, Wash., Portland, Oreg., and Winnemucca, Nev. Between the second and third ridge we have the following line of lowest values: Havre, Mont., 0.061, Rapid City, S. Dak., 0.082, North Platte, Neb., 0.101, Dodge, Kan., 0.126, Amarillo, Tex., 0.135 and El Paso, Tex., 0.150. And finally from the Great Lakes, where the amplitudes are lowest (Sault Ste. Marie, Mich., 0.071), the values are small along the Appalachians as far south as Atlanta, Ga., where the amplitude is only 0.119.

To summarize therefore: there is a minimum of annual variation in the north and a maximum in the south, and, across the United States, a fork of three depressions of these values extends from the north and a fork of four ridges from the south. Moreover, in all probability a correlation exists with the topographical conditions. The number of barometric stations is insufficient to decide upon this question. Notice now that—evidently—it is along the ridges of greatest annual variation that the air is the most drawn and rejected, periodically, with the changes of the seasons.

I have drawn two other maps which it is also not necessary to reproduce. These maps give the month of occurrence of the yearly maximum and minimum. If the annual variation were represented everywhere by a simple oscillation with one maximum and one minimum, things would be simple. But it is not so. Certain areas have two maxima and two minima, and for some places the variation is even more complicated, so much so that it is difficult to decide. The monthly departures for Seattle may serve as an example of an unsettled yearly variation: —41, +17, —38, +32, —10, +22, +22, —27, —24, +20, —3, +27. These figures are the means of only seven years of observations. But the comparison of the figures for these different years shows that the yearly variation is not settled one way or the other.

I will now consider the geographical distribution of the maxima. Their earliest appearance is in the plateau region: in July at Helena, Mont., and Amarillo, Tex.; in August at Lander, Cheyenne, Denver and Pueblo; in September at Santa Fé and Rapid City; in October at Havre, Mont.; in November all around and enclosing the preceding area, at Spokane, Walla Walla, Boise, Salt Lake City, Flagstaff (a secondary maximum) and, on the other side, at Dodge, North Platte and Williston, N. Dak.

It is of interest to notice that the early appearance of the maximum is not a simple question of altitude. The El Paso station is 3,762 feet above sea level, and the variation is regular and simple: a maximum in December, followed by a gradual decrease until May, and, from then on until the end of the year, the increase is progressive; there is no secondary maximum or minimum. In Phoenix, Ariz., only 1,108 feet high, the July maximum is slightly marked, the figures for June, July and August being —127, —83, —89. This secondary maximum in July is well marked on the annual variation curves of other stations: Baker City, Winnemucca, Carson City, and, on the other side, Dodge and Pierre, for example. But the principal maximum occurs in December.

The December maximum is characteristic for California and also for the margin of the plateaus at Phoenix, Ariz., El Paso, San Antonio and Abilene, Tex., and farther north, towards the northeast of Kansas, and from the Gulf of Mexico on both sides of the Appalachians as far north as Pittsburg, Pa. South and north of this December area the maximum occurs in January at San Diego, Cal., Galveston, Tex., and in Louisiana, Florida and Georgia. The same occurs farther south in Havana, whereas in Santiago de Cuba and Porto Rico the maximum occurs in February. East of the Missouri River, especially in Minnesota, Iowa and Illinois, the maximum of the yearly variation occurs in January; also on the Atlantic coast and in the intermediate region of the Great Lakes. Farther north, in Boston, Portland and Eastport, we note a perfectly characteristic maximum in September and but a secondary maximum in January. Finally, in Marquette, Escanaba and Alpena the maximum occurs in February and in Sault Ste. Marie as late as April. The secondary July maximum of Key West and other southern stations occurs in August in Jacksonville, and farther north and west many stations display a secondary maximum in September, the month of the principal maximum of the Lake region.

The map giving the occurrence of the yearly minima is also of some interest. The earliest occurrence of the minimum is in March. The area where the lowest values fall in March forms a strip crossing the plateau region from Helena, Mont., towards Amarillo, Tex. The other stations with a well-pronounced March minimum are Baker City, Lander, Cheyenne, Denver, Pueblo and Santa Fe. But in Carson City the principal minimum also occurs in March; and at the stations in Oregon and Washington, where the annual variation is more complicated, the month of March forms one of the minima.

Around the March area we have a few stations where the minimum occurs in April: Flagstaff, Ariz., and North Platte, Neb., for example. In Salt Lake City the barometer is lowest in May, also in Winnemucca, Nev., and San Diego de Obispo, Cal.; but there we have a second minimum in August. This August minimum is to a certain extent characteristic for California, Fresno with a July minimum and San Diego, where the minimum occurs as late as September, forming the exceptions.

South, north and east of the area where the minimum occurs in March we have a great predominance of stations with a May minimum. In North Dakota, Minnesota and Wisconsin the minimum occurs in June, and in the northeastern states, where the annual variation is more complicated, July forms one of the minima. A double oscillation is also very well developed in the southern states, and if we look more attentively at the details we note that this double oscillation can to a certain extent be explained as follows: A first minimum propagates itself from the West Indies towards the north across the Atlantic states, and from the Rocky Mountains towards the Lakes and Canada. The second minimum is this same minimum coming back from the north towards the south.

Going north we may cite: April minimum over Porto Rico and the southern part of Cuba, Florida and all of the Middle States with an extension towards the Lakes and the Atlantic coast as far as Norfolk; June minimum at some of the New England stations, the northwestern states cited above and Canada: going back south: July minimum over New York, Pennsylvania and New Jersey; in August a secondary minimum well pronounced towards the south; in September the principal minimum at Jacksonville and Tampa; in October at Jupiter and Havana; and, finally, in November over

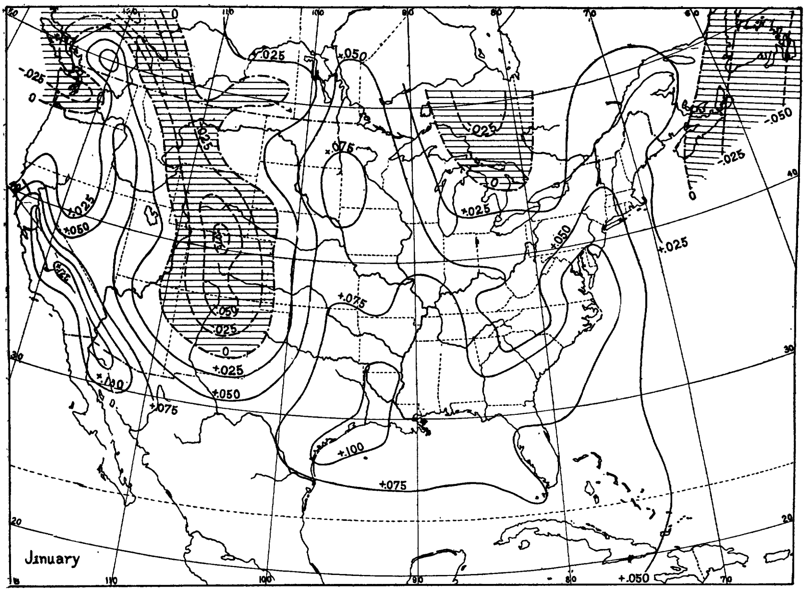
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Fig. 2

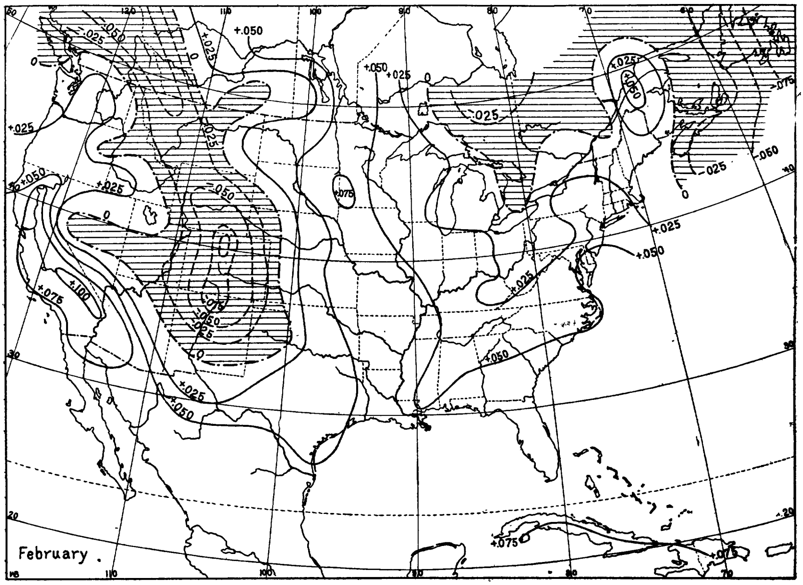
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Fig. 3

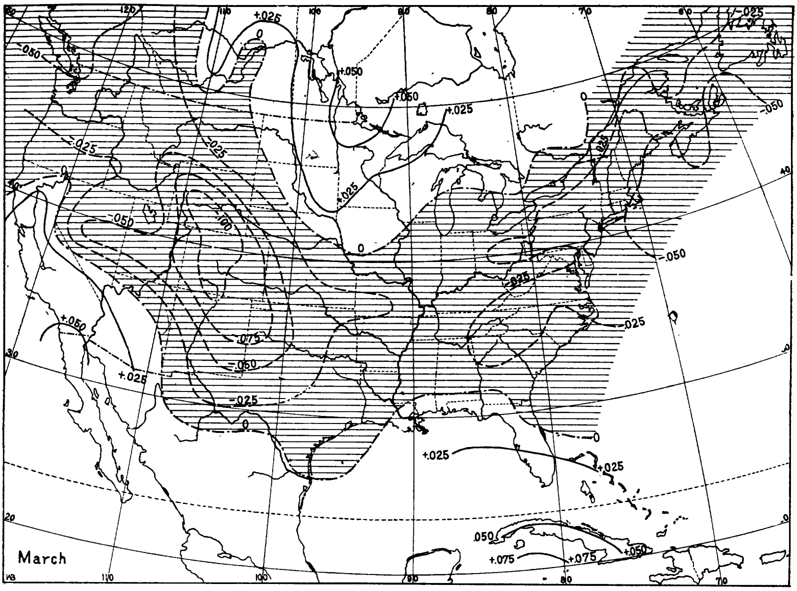
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FIG. 4

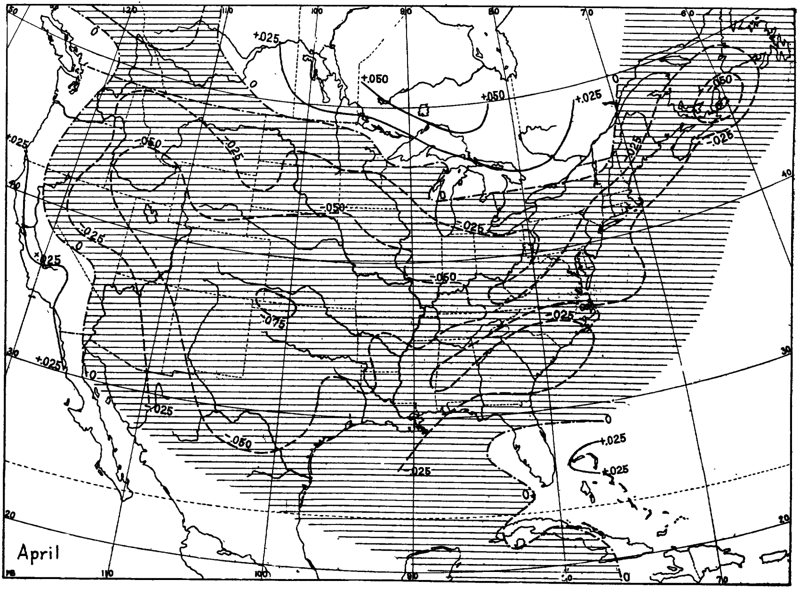
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FIG. 5

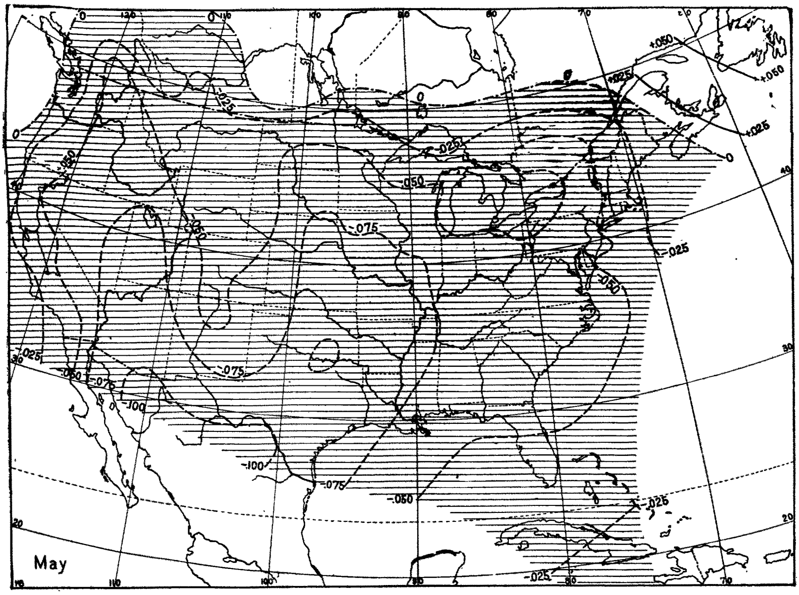
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FIG. 6

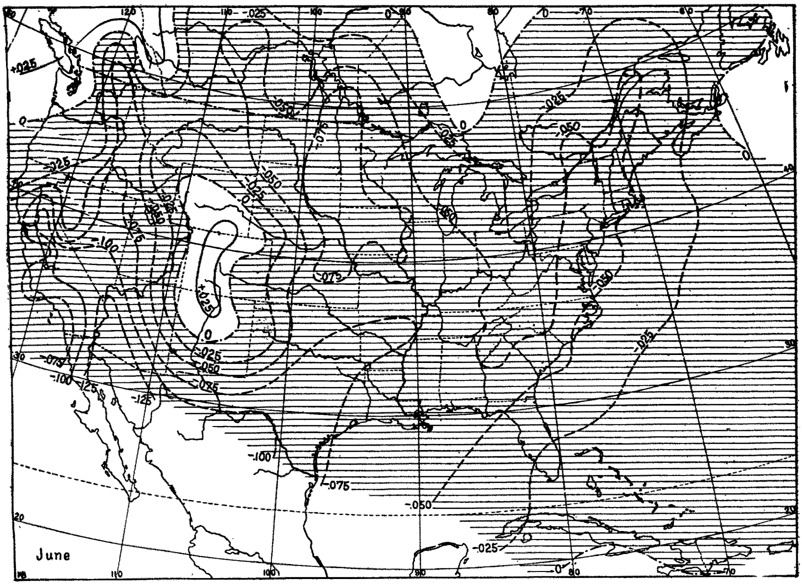
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FIG. 7

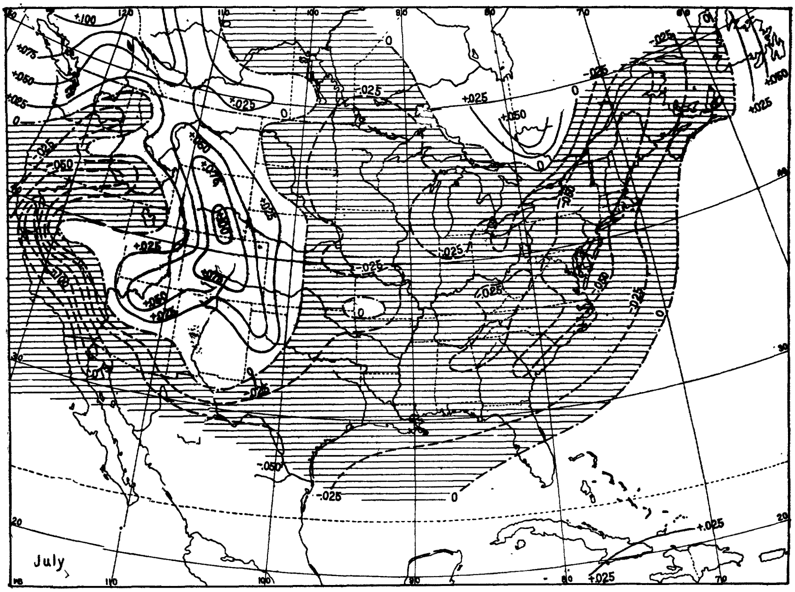
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FIG. 8

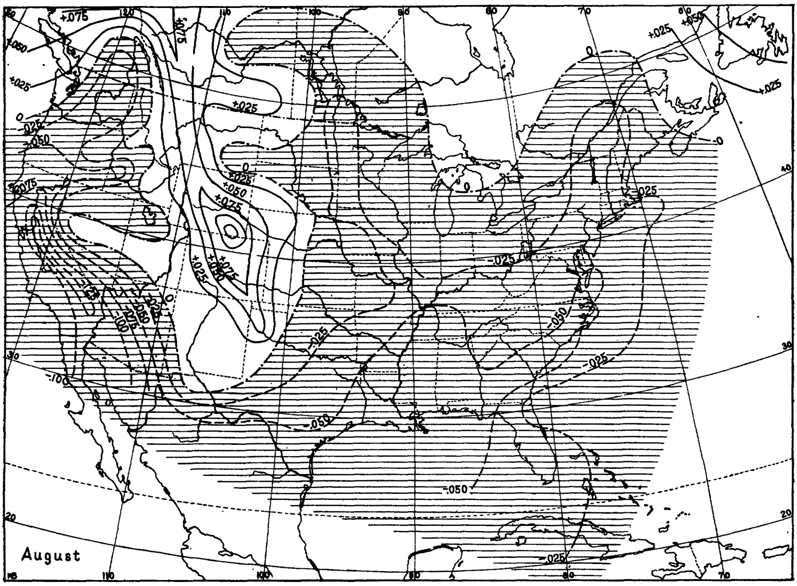
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FIG. 9

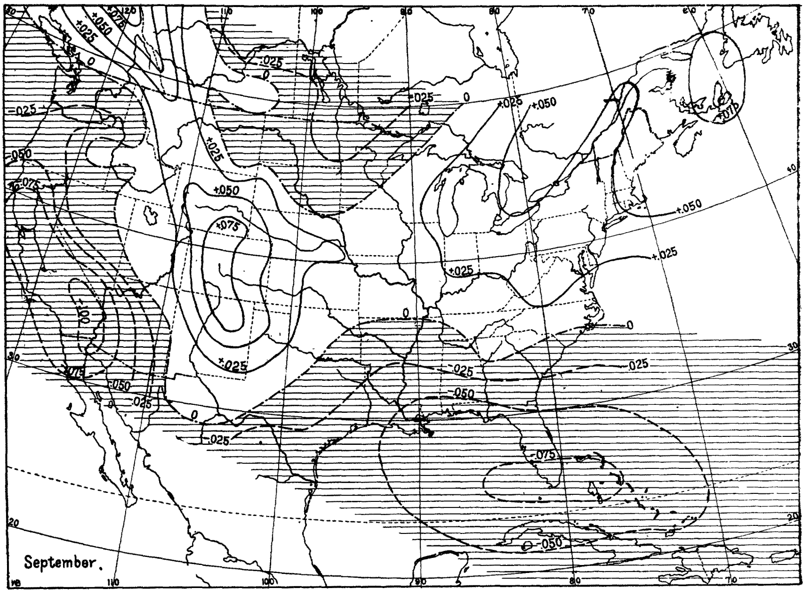
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FIG. 10

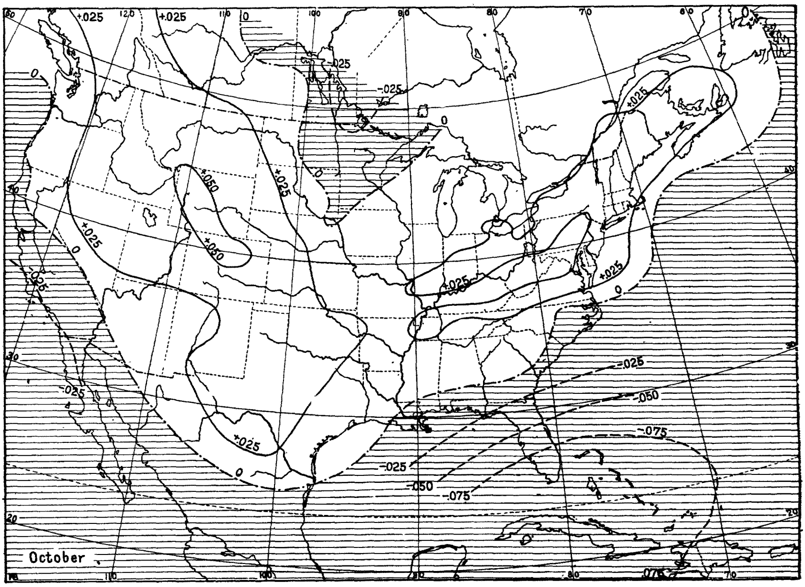
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FIG. 11

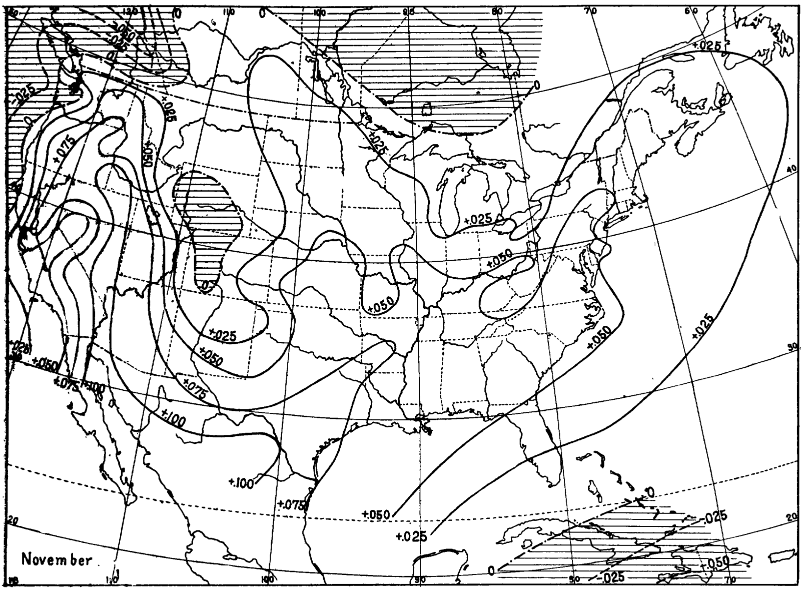
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FIG. 12

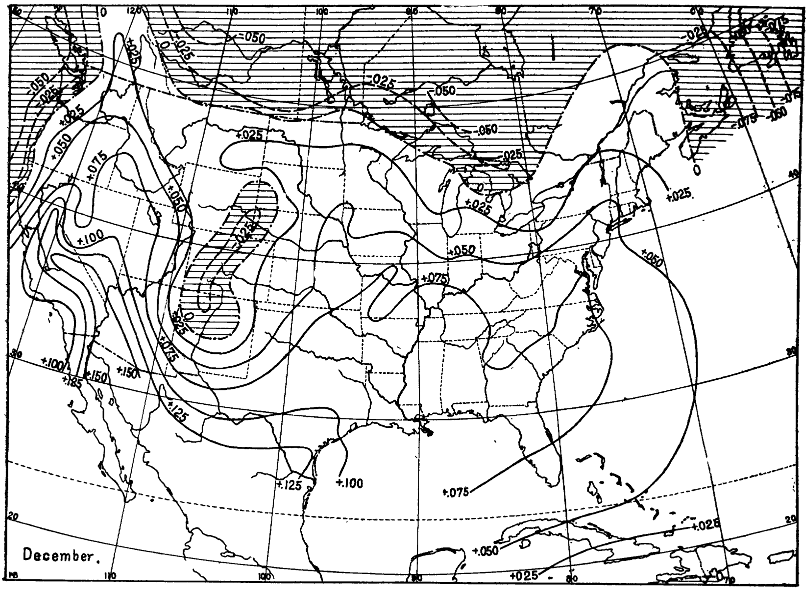
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FIG. 13

Porto Rico. Therefore it is a wave movement to and fro, a seasonal migration.

In order to study this migration I have drawn maps of the departures of the mean monthly means from the normal atmospheric pressure (Figs. 2 to 13). On the maps the equi-departure lines are drawn for every 0.025 of an inch. The positive areas indicate the excess of pressure above the normal annual mean and the shaded negative areas the deficit below the normal. These maps represent therefore the real transport of the air masses quantitatively.

The comparison of the maps naturally leads to many remarks. I will mention but a few points which are of more general interest.

As I pointed out before, the minimum of the yearly variation occurs in January at the summit of Pike's Peak. At the stations of the plateau region where the annual minimum occurs earliest it is only in March that we observe it. Now why is this so? The maps explain the fact. In January, when the temperature is lowest, the area of negative values at the plateau stations is due, exactly as at the summit of Pike's Peak, to the greater density of the air: in other words the air has to flow down the slopes in order to be maintained in equilibrium, while on both sides, east and west, the pressure is much above the normal. In February the pressure decreases and in March it is below the normal. The base on which the layers of air repose on the plateau has gone down, and the decrease of pressure below causes the March minimum above. In reality the minimum occurs in January; it is retarded till March mechanically.

Now, why does the yearly minimum migrate as I have shown? The maps will give us an answer. From the maps I have prepared cross-sections along a straight line from Sault Ste. Marie to San Luis Obispo. The following diagram (Fig. 14) gives the sections for the months from January to June. First of all we see that the difference between the depression and the ridges is greatest in January and diminishes until May. We also see at once why it is that the lowest value is observed in March. But in place of the occurrence of this minimum we notice in May and June the formation and development of a maximum. Referring to the maps we find that this maximum occurs in August. On the section there is a shifting of the minimum in April. In May we have two minima. In June the growing maximum shifts these minima farther apart, one to the northeast and the other to the southwest. The March minimum of the plateaus, which is a mechanically retarded January mountain minimum, has therefore a marked influence on the occurrence of the annual minimum in the surrounding region. The minimum has to migrate; the maximum also. The sections for the months from August to December (not published here) show this very well.

The maps measured with a planimeter could serve to estimate the quantities of air which are displaced one way or another month by month. At least one figure is of great general interest. It is the figure expressing the weight of the total mass of air going from and coming back over the area of the United States, the difference between the mean values of the months of highest and lowest atmospheric pressure.

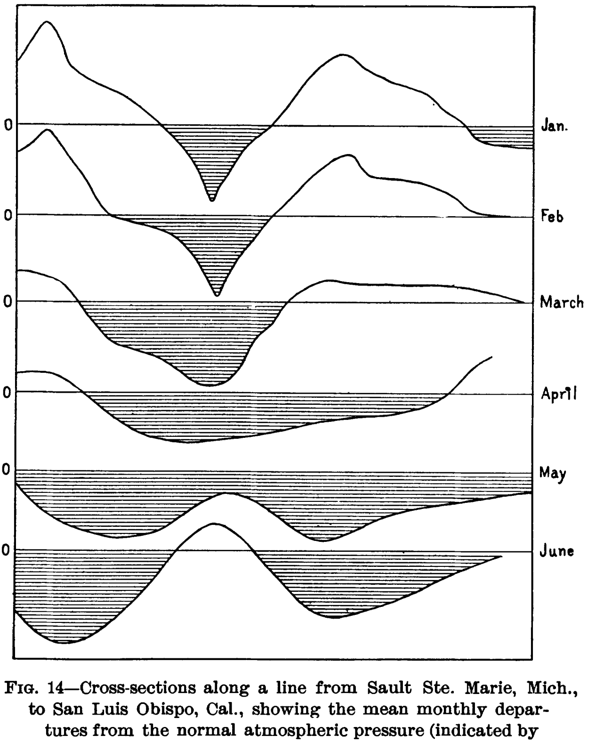

Fig. 14—Cross-sections along a line from Sault Ste. Marie, Mich., to San Luis Obispo, Cal., showing the mean monthly departures from the normal atmospheric pressure (indicated by the 0 line) from January to June. Based on Figs. 2 to 7.

As planimetric measurements require more time than I can afford on this particular question—which interests me but indirectly—I have simply taken the figures from Table 54 in Bigelow's report. Bigelow calculated the mean departures of the ten groups of stations and then computed the means. The extreme means are +0.045, in December, and —0.044, in May. The difference in the pressure over the United States between May and December is therefore 0.089. This figure is too small inasmuch as Bigelow's groups of stations cover unequal areas. Nevertheless let us imagine a difference of 0.090 inches (or 2.3 mm.) of mercury. The weight of one cubic centimeter of mercury being 13.5956 gr.,[6] the weight of a column 2.3 mm. high is 3.126988 gr. per square centimeter. In other words the difference in atmospheric pressure between the months of December and May is equivalent to the weight of a column of water at least 3 centimeters high. This amounts to 30,000 (metric) tons per square kilometer or 235,181,490,000 tons for the surface area of the United States.[7]

It is this weight of air (equivalent to the weight of 235 cubic kilometers of water) which periodically moves away and comes back. The maps show the details of the displacements.

Let us consider the monthly distribution of pressure along the 90th meridian. The cross-sections for the months from August to December show that the high pressure area moves from north to south. In August pressure is above the normal on Lake Superior; in September the crest of the positive wave is near Dubuque, in October it is over St. Louis, in November at Memphis and in December at New Orleans. From August to December the positive departures at the crest increase and at the same time cover a progressively wider area. The surplus of air which makes this wave comes, as the maps show very well, from the northeast and the southwest. There is a double movement of the air masses: the air necessary to increase the pressure comes first from the northeast, the Atlantic, then from the southwest, the Pacific Ocean west of Mexico, and this is probably the reason why the crest has to move from north to south along the 90th meridian.

There are many minor phenomena of this same kind for which a careful study gives an easy explanation. Studied from another point of view, especially in connection with the data on wind and rainfall, I think the maps would give information relating to the study of crops. The data I utilized to draw the maps were averages. In the case of particular years the departures may be very different from what they are on the average.

In these Studies on Climate and Crops I will have to come back to the investigation of the annual variation of atmospheric pressure and examine the subject from the point of view of abnormal conditions existing in particular years. As an example I will cite the differences of the mean yearly pressures observed at Cheyenne and San Francisco. The smallest figures are those of 1878 and 1889, years of minima of sunspots. The largest difference occurs in 1893, a year of maximum of sunspots. One may ask in what particulars the annual variation of atmospheric pressure in 1893 was different from the average.

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[6] Smithsonian Geographical Tables, 1906.

[7] According to the Statistical Abstract the surface area of the United States is 3,026,789 square miles.

As we have seen, the annual ebb and flow of the atmosphere over the North American continent is a phenomenon far less complicated than it seemed to be. We may hope therefore that it will not be too difficult to discern the superposition of abnormal waves, due to the variations of solar activity, upon the normal waves due to the changes of the seasons.

DOBBS FERRY, N. Y., June 23, 1912.

SCOTT'S LAST EXPEDITION: A REVIEW*

By WILLIAM HERBERT HOBBS

Eight years ago, after the return of Scott's first expedition, appeared "The Voyage of the 'Discovery' " in two large volumes. This was followed in 1910 by the report of the British expedition under Lieut., now Sir Ernest Shackleton, likewise in two volumes of similar size entitled "The Heart of the Antarctic." The two new volumes which describe Scott's second and last expedition maintain the form and the general external appearance of their predecessors, though surpassing them—as they do, indeed, all other reports of similar purpose—in the perfection and the beauty of their illustrations.

Taken together these six volumes of narrative and scientific observation are without a rival and should be the cause of just pride for every compatriot of the great leaders, Scott and Shackleton.

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*Scott's Last Expedition: Vol. I Being the Journals of Captain R. F. Scott (xxiv and 446 pp); Vol. II Being the Reports of the Journeys and the Scientific Work Undertaken by Dr. E. A. Wilson and the Surviving Members of the Expedition (xvi and 376 pp.) Maps, ills , index. Arranged by Leonard Huxley with a preface by Sir Clements R. Markham. Dodd, Mead & Co., New York, 1913. $10.00. 9½ x 6½.